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A SOUTH AFRICAN REVIEW OF HARMONIC EMISSION LEVEL ASSESSMENT AS PER IEC61000-3-6

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SUMMARY

Large-scale renewable power producing plants are being integrated into South African networks. Network operators need to ensure that Renewable Power Plants (RPP) do not negatively affect the power quality levels of their networks, as harmonics amongst others could become a concern.

IEC 61000-3-6 details a method for allocating voltage harmonic emission limits for distorting loads. This method works well for the allocation of emission limits; however it does not address the management of harmonic emissions once a plant is connected to the network. The management of harmonic emissions requires that network operators measure or quantify the emissions from loads and generators to determine compliance. Post-connection quantification of harmonic levels and compliance is a challenge for network operators. The question asked is "How should a network operator measure/quantify the harmonic emissions of a load/generator to establish compliance with the calculated limits as per IEC 61000-3-6".

This paper reviews within a South African context methods of assessing harmonic emission levels and then evaluates these methods by means of field data. Opportunities for improvement are identified and operational requirements discussed.

KEYWORDS

Harmonic emission, harmonic vector method, harmonic active power method, grid compliance

Introduction

In 2009 South Africa opened its Transmission and Distribution networks to RPP's to aid in the supply of much needed electricity generation capacity and to reduce the carbon footprint of electrical generation. To manage the addition of the RPP's South Africa developed the "Grid connection code for (RPPs) connected to the Transmission System (TS) or Distribution System (DS) in South Africa" [1]. Part of this document specify the management of Power Quality (PQ) and what the RPP's and utility obligations are with respect to PQ. The document states that the electrical utility will supply the RPP with apportioned emission values to which the RPP's compliance will be assessed.

IEC 61000-3-6 [2] describe a method to allocate harmonic emission to a harmonic distorting load depending on the network parameters and the size of the distorting load or source that is to be connected. This can support the utility in containing waveform distortion at the Point of Common Coupling (PCC) within planning levels.

While the allocation of the emission for a specific load or renewable generator seems clearly defined, the challenge lies in determining if the load or generator is meeting the emission limits that the utility has specified for Grid Code Compliance. The measurement of the emission contributed by a single source of distortion is a challenge in a real-life power system.With different sources of distortion located all over a network and a continous changing network configuration, single-point measurements of harmonic active power (for example) cannot be used in the assessment of harmonic emission contributed only by the distorting source under investigation [3].

This paper first analyse the fundamental principles pertaining to emission, the assessment thereof based on a practical South African case study and then discuss the results in context of the scientific and metrological requirements of measuring emission at sources of renewable energy.

Harmonic emission: brief overview of the IEC61000-3-6 definition

IEC61000-3-6 defines emission as a phenomenon by which electromagnetic energy emanates from a source of electromagnetic disturbance. The document further defines the indivudal harmonic emission level ($\boldsymbol{U}_{hi}$) as the harmonic voltage (or current) phasor at each harmonic number h at a PCC as illustrated by Fig. 1 below.

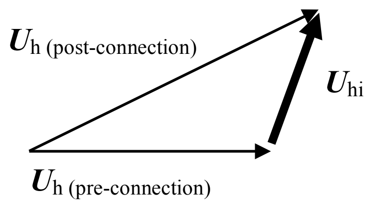

Fig. 1. Illustration of harmonic emission Vector $\boldsymbol{U}_{hi}$ [2]

Where;

$\boldsymbol{U}_{h(pre\text{-}connection)}$	The distortion at a Point of Connection (PoC) before the RPP or load is connected.
$\boldsymbol{U}_{h(pos\text{-}connection)}$	The distortion at that PoC after the RPP or load is connected.

The vector difference of the post-connection and pre-connection phasor values is considered as the emission level that the RPP or load is injecting back into the network.

The calculation of emission in Fig. 1 requires knowledge on the angle between $\boldsymbol{U}_{h(pre\text{-}connection)}$ and $\boldsymbol{U}_{h(pos\text{-} connection)}$. It is not possible to directly measure this angle. The IEC61000-3-6 describes a general summation law (1) to be used by engineers in the estimation of the emission value, $\boldsymbol{U}_{hi.}$

It is a practical approach as most modern day PQ recorders are able to measure the magnitude of the voltage and current harmonic components, but the uncertainty in measurement of the magnitude become worse with harmonic number and with the reduction of signal-to-noise ratio at the relatively low levels of harmonics at higher orders. The angle of harmonic phasors is even more compromised by the performance of Current Transducers (CT's) and Voltage Transducers (VT's).

The IEC61000-3-6 proposed an engineering solution to the measurement uncertainties by application of (1), known as the general summation law [4]:

$$U_h = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} \tag{1}$$

Where;

U_h	is the magnitude of the harmonic voltage,
U_{hi}	is the magnitude of the individual harmonic emission level
α	is the summation exponent.

An α value of 1 means that the harmonic values will add up linearly, a value of 2 mean that the values will add up orthogonally. The α exponent recognises that harmonic components add up differently due to the different harmonic phase angles. IEC61000-3-6 indicative values are listed below in Table 1.

harmonic order	α
h < 5	1
5 ≤ h ≤ 10	1.4
h > 10	2

Table 1: Summation exponents for harmonics (indicative values)

Equation (1) is then applied in (2) to calculate the emission level based on the magnitude of the pre- and post-connection harmonic values. The same α exponents as given in Table 1 are used.

$$U_{hi} = \sqrt[\alpha]{U_{post\ connection}^{\alpha} - U_{pre\ connection}^{\alpha}} \tag{2}$$

Harmonic emission assessment by the harmonic vector method: CIGRE/CIRED joint working group C4-109

The CIGRE/CIRED joint working group C4-109 [5], [6], [7] tabled the harmonic vector method to determine the emission level from a customer installation by making use of a single point measurement at the Point of Common Coupling (PCC) as shown in Fig. 2. The advantage of this method is that it is non-intrusive to the network as no switching or disconnection is required to determine the emission levels at a specific installation.

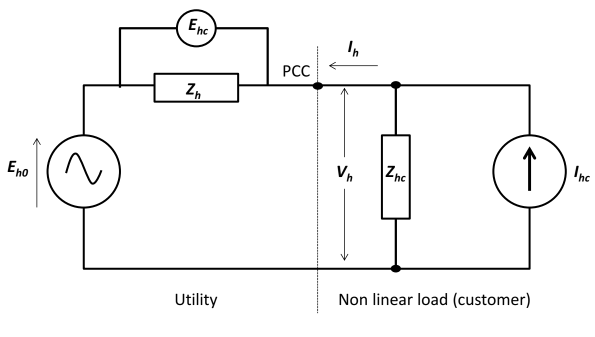

Fig 2. Equivalent network diagram for the definition of the harmonic emission level at the PCC [5]

Where;

$\boldsymbol{V}_h$	The harmonic voltage phasor at the PCC.
$\boldsymbol{I}_h$	The harmonic current phasor.
$\boldsymbol{E}_{h0}$	The background (in the supply system) harmonic voltage phasor.
$\boldsymbol{Z}_h$	The complex supply impedance.
$\boldsymbol{Z}_{hc}$	The complex impedance consumer installation.
$\boldsymbol{I}_{hc}$	The harmonic sources present in the consumer's installation.
$\boldsymbol{E}_{hc}$	The voltage harmonic emission phasor.

A similar approach as in Fig. 1 is then applied by the CIGRE/CIRED C4-109 working group in Fig. 2 to illustrate the principle of harmonic emission. The current harmonic phasor $\boldsymbol{I}_h$ is used additionally.

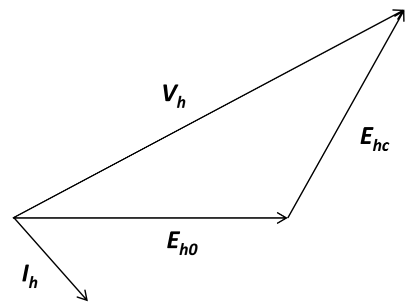

Fig. 3: CIGRE/CIRED C4-109 definition of the individual customer harmonic emission [5].

In this method it is assumed that the current harmonic flows from the load into the network, i.e. the network has zero harmonic contribution at the PCC. The voltage emission $\boldsymbol{E}_{hc}$ is the voltage across the network impedance $\boldsymbol{Z}_h$ due to the harmonic current $\boldsymbol{I}_h$ flowing through this impedance. This method holds true when $\boldsymbol{V}_h > \boldsymbol{E}_{h0}$. The equation used for $\boldsymbol{I}_h$, is as follows:

$$\boldsymbol{I}_h = \boldsymbol{I}_{hc}\frac{\boldsymbol{Z}_{hc}}{\boldsymbol{Z}_h+\boldsymbol{Z}_{hc}} - \frac{\boldsymbol{E}_{h0}}{\boldsymbol{Z}_h+\boldsymbol{Z}_{hc}} \tag{3}$$

The harmonic voltage emission is determined by:

$$\boldsymbol{E}_{hc} = \boldsymbol{Z}_h\boldsymbol{I}_h = \boldsymbol{V}_h - \boldsymbol{E}_{h0} \tag{4}$$

This method requires the network and load impedances to calculate the voltage harmonic emission value. Load impedance at a source of renewable energy can introduce an unknown as it can be non-linear and continuously changing due to operation of the power electronics used by a source of renewable energy in connecting to the distribution network. Network impedance can be estimated by the fault level at the PoC.

Fig. 4 illustrates the CIGRE/CIRED C4-109 workgroup principle by means of a scatter plot. If the scatter plot values are concentrated between the loci of the impedance lines, then both the load and the supply network contribute to harmonic distortion at the PCC. If the scatter plot values are concentrated around the supply system impedance, then the load dominates the harmonic distortion. If the scatter points are concentrated around the load (customer/PV plant) impedance, then the system dominates the harmonic distortion at the PCC.

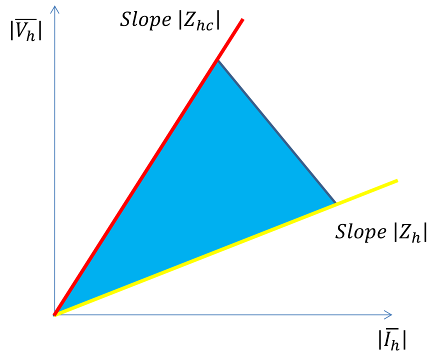

Fig. 4. Principle of the CIGRE/CIRED C4-109 method [5]

Application of the harmonic vector method

Practical measurements were obtained at a photovoltaic plant in South Africa and the harmonic vector method then evaluated as a method to assess harmonic emission. The scatter plots shown in Fig. 5 and 6 represent the distribution of harmonic voltage against harmonic current values. Harmonic emission voltage levels were derived from the product of the reference (network) impedance at a harmonic number and the 95th percentile of harmonic current.

The recorded data used in this analysis are 10-min aggregated data recorded to the Class A requirements of IEC61000-4-30 Ed 3 [8]. The PV plant impedance cannot be graphed due to the reasons above. But, according to [7], the supply network impedance is sufficient to determine harmonic emission levels.

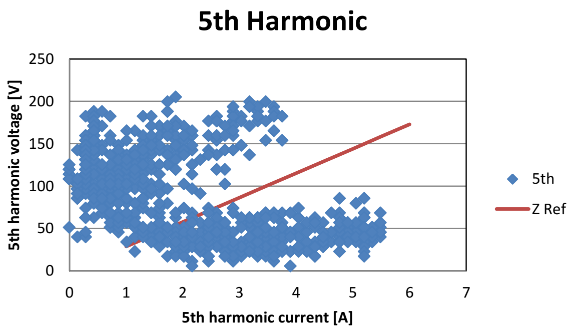

Fig. 5: 5th harmonic scatter plot

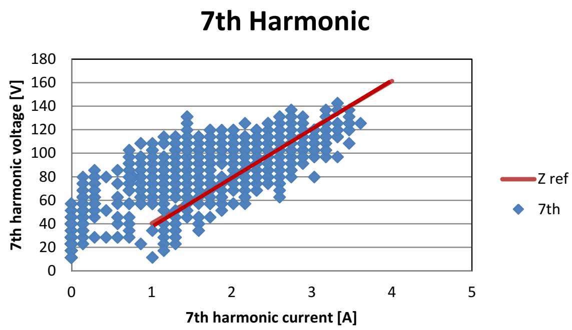

Fig. 6: 7th harmonic scatter plot

Discussion of results

The results in Fig. 5 and 6 indicate that the harmonic vector method does further an understanding to how the PV plant and the distribution network contributes to harmonic voltages at the PCC. An important constraint to the assessment of harmonic emission by single-point measurements is evident in Fig. 5. Voltage harmonic and current harmonic values are both concentrated in the horizontal and vertical direction indicating that both the distribution network and the PV plant have the ability to contribute to emission at the 5th harmonic.

It is a practical proof that it is impossible by single-point measurements to isolate the contribution of the PV plant to the 5th harmonic components at the PCC. The PV plant can “consume” harmonic current but has the ability to also inject harmonic current. It is imperative to find the direction of the harmonic current in order to distinguish between “inject” (emission) and “absorb” and not straightforward.

The 7th harmonic values behave differently. It is spread around the impedance locus of the distribution network indicating that the PV plant dominates the contribution to emission at the 7th harmonic. It is however not conclusive as to be an exact quantification of how much of the voltage distortion at the PCC was due to the 7th harmonic voltage as contributed by the PV plant alone.

With only one source of waveform distortion (e.g. a PV plant) exists in an electrical network, the harmonic active power was shown to be useful in the localisation of the source of distortion [9]. With multiple sources of distortion located all over the network, it is not possible to use single-point measurements to localise a source of waveform distortion [3]. The practical significance to the assessment of harmonic emission seems to be that measurement methodologies cannot be based on single-point measurements.

A pragmatic approach to an engineering solution is however needed and has to be the focus of applied research. Harmonic active power per harmonic order (P_h) is calculated from the fundamental definition of real power:

$$P_h = V_h I_h \cos(\emptyset_h) \tag{5}$$

Where;

V_h	is the rms value of the harmonic voltage phasor $\boldsymbol{V}_h$ at harmonic order h
I_h	is the rms value of the harmonic current phasor $\boldsymbol{I}_h$ at harmonic order h
$\emptyset_h$	is the phase angle between $\boldsymbol{V}_h$ and $\boldsymbol{I}_h$

If harmonic active powers over all harmonic components are summated, the concept of *Joint Harmonic Active Power* (*JHAP*) can be defined:

$$JHAP = \sum_{h \neq 1}^{N} V_h I_h \cos(\emptyset_h) \tag{6}$$

If the direction of the active power at the fundamental frequency is by definition a negative value at the source (or PV plant) as it is "injected"/delivered to the distribution network, harmonic active power with a similar negative sign can be considered to be also "injected" into the distribution network. This concept of "injection" is the basis of the concern to harmonic emission, as the harmonic voltage will increase at the PCC when harmonic currents are injected.

Nonlinear loads (and sources such as a PV plant) have the ability to exchange harmonic active power. This exchange is the result of continuous changes in network and source impedance. Each PV plant is operated according to local control settings (causing a change in the equivalent impedance of the PV plant) and the supply network so not remain static. This phenomenon renders single-point measurements ineffective as the recordings at a specific time reflect the interaction of the source of distortion with the network during the time of investigation.

Harmonic emission assessment: Grid code compliance considerations

The distribution system owner (such as Eskom) requires evidence from the RPP that compliance to the grid code was achieved. Investment for the RPP is at risk if the harmonic assessment cannot prove compliance to allocated emission values.

The scientific constraints to single-point measurements used in the assessment of harmonic emission could benefit from synchronous measurements taken at all nodes pertaining to the source of distortion. Instrumentation needed to achieve this, is not readily available. An engineering approach, which further useful results in the assessment of harmonics and that are fair to both the network operator and the RPP, is needed. A number of operational aspects have to be taken into account:

- Some RPP's are connected to dedicated substations while others connect onto existing substations which already have other non-linear loads connected. Capacitor banks connected onto these nodes can further complicate matters due to the low impedance paths for harmonics created by capacitor banks and possible resonant amplification.
- The summation of harmonics with random phase angles [4] may cause some harmonics to be "cancelled" between harmonic sources at the node of assessment, but could later on summate when the phase angles change.
- The general summation law given in the IEC61000-3-6 report yields valid results provided there is only one harmonic source at the PCC and if all harmonics contributed emanate from that source (no variable harmonic content in the supply network). Pre-connection measurements to be used in the comparison could represent different network conditions to the network conditions during the post-connection phase.
- Based on the results obtained by Fig. 5 and 6, the CIGRE/CIRED harmonic vector method do add understanding to the emission of a source of distortion (PV plant in this case), but is not conclusive as to how much of the waveform distortion has to be attributed to the PV plant and how much due to the background distortion in the supply network.

Application of aggregated values for harmonic active power in harmonic assessment

The aggregation principle of PQ parameters based on the 10/12 cycle Class A measurement requirements of the IEC61000-4-30 edition 3 can be used as a standardised approach to the parameters used in harmonic assessment. A methodology has to be agreed upon under the scientific constraints discussed above. Results are presented below based on a discriminative approach in the application of harmonic assessment for compliance to the "Grid connection code for Renewable Power Plants (RPP's) connected to the electricity Transmission System (TS) or the Distribution System (DS) in South Africa".

A discriminative approach to the assessment of harmonic emission is demonstrated below, but only for the 5th harmonic. Observe the relation between the 5th harmonic voltage and the 5th harmonic current shown in Fig. 7.

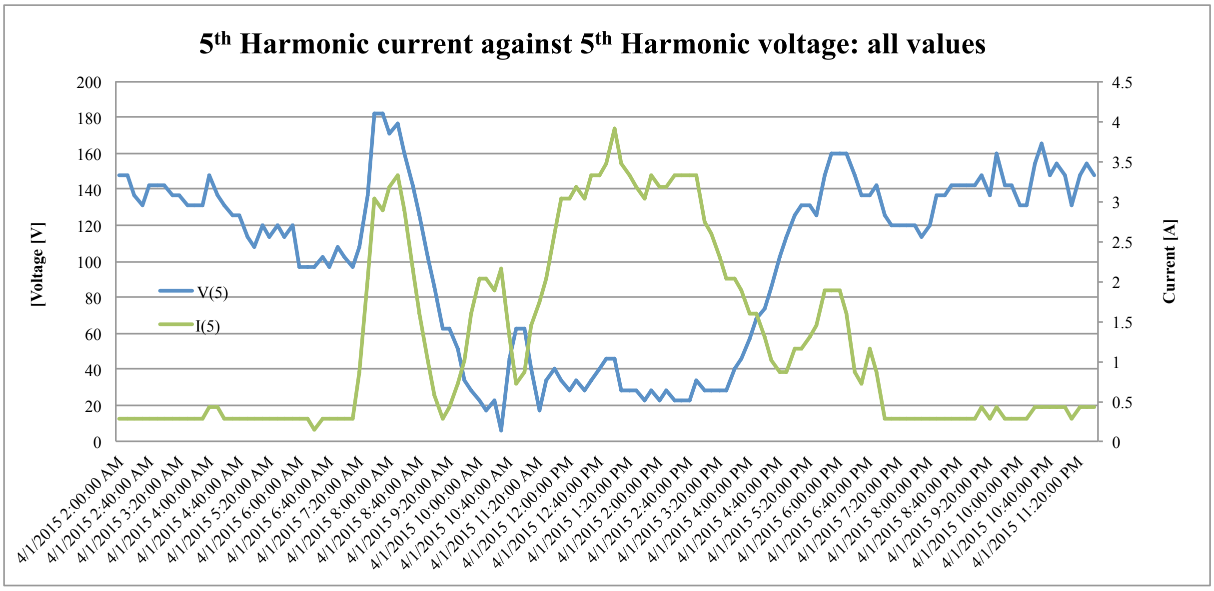

Fig. 7: The relation between 5th harmonic voltage and the 5th harmonic current at a PV plant, all values recorded are shown.

During the night when the PV plant is not producing any energy, the 5th harmonic voltage is clearly unrelated to the 5th harmonic current. The challenge is to assess how much of the 5th harmonic voltage was contributed by the PV plant during the day.

If an aggregated value for harmonic active power such as the 10-min values can be regarded as a fair reflection of the interaction of the PV plant during that 10 minutes, and then using the principle that when the harmonic active power is in the same direction than the active power at the fundamental frequency, then that harmonic active power value was "injected" into the network, it can be classified as harmonic "emission".

Sorting the harmonic current values, which represent the instances when harmonic active power is opposite to the direction of fundamental frequency active power, resulted in Fig. 7. Positive values for harmonic active power in this case signify instances when harmonic active power was consumed by the PV plant. Such instances cannot be classified as emission.

Consuming harmonic active power is expected to reduce the harmonic voltage. This is indeed noted in Fig. 7. From around 11h00 until 16h00, the increase in harmonic current correlate to a reduction in harmonic voltage which benefits the utility. Instances exist where the increase of harmonic current correlate to an increase in harmonic voltage. This can be explained by the lower values of energy being produced by the PV plant and due to the changed relative impedance presented to the supply network, the contribution of 5th harmonic voltage by the supply system dominates.

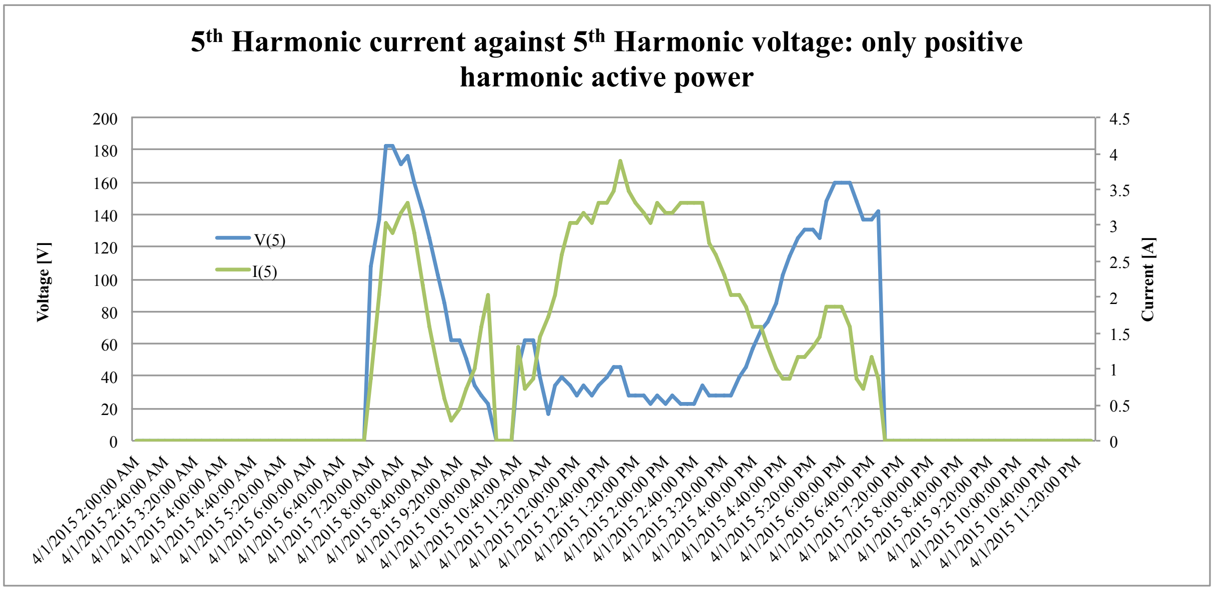

Fig. 8: The relation between 5th harmonic voltage and the 5th harmonic current at a PV plant, values shown are only when harmonic active power is positive.

The results of a discriminative approach to the assessment of harmonic emission based on the principle demonstrated in Fig. 7 and 8 are listed in Table 2.

Harmonic impedance (*h*=5)	86.4 Ω
Harmonic voltage emission allocated	0.028 p.u.
Harmonic voltage emission allocated at 22 kV	355.6 V
Harmonic current emission allocated	4.1 A
Harmonic current measured, maximum value based on emission values only	3.8 A
Harmonic current measured, maximum value based on all values	5.5 A
Harmonic current measured, maximum value based on emission values only, 95th percentile	0.4 A
Harmonic current measured, maximum value based on all values, 95th percentile	4.3 A

Table 2: Results of harmonic assessment, 5th harmonic

This PV plant will not comply with the limit value in emission allocated when all values recorded are used, based on both the maximum value and the 95th percentile as listed in Table 2. It will only comply when discrimination is done between the concept of emission and "absorption" of harmonics. It is therefore postulated that the discriminative approach represent the "fair" assessment of harmonic assessment.

Conclusion

The calculation of the harmonic emission levels has to be fair and equitable. An improvement to existing measurement methodologies is needed. The goal of harmonic assessment is to evaluate the contribution of a source (PV plant in this case) to the waveform distortion at the PCC as the network operator has the obligation to maintain waveform distortion well within the planning level pertaining.

Interaction between non-linear loads distributed all over the distribution network, the continuous change in network impedance and configuration all necessitates that single-point measurements used in the assessment of harmonic emission have to be carefully evaluated. Further research is required.

Possible improvements to existing international and local methodologies could be:

- The use of simultaneous measurements at all nodes of interest.
- The use of simultaneous measurements across an impedance between the PV plant and the PCC to better understand the direction of the harmonic current.
- The exact definition of harmonic "emission" to compliment the data analysis, such as the discriminative approach presented in this paper.

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